

Future of short pulse x-ray studies
for
**Warm Dense Matter
and
Plasma-Related Research**

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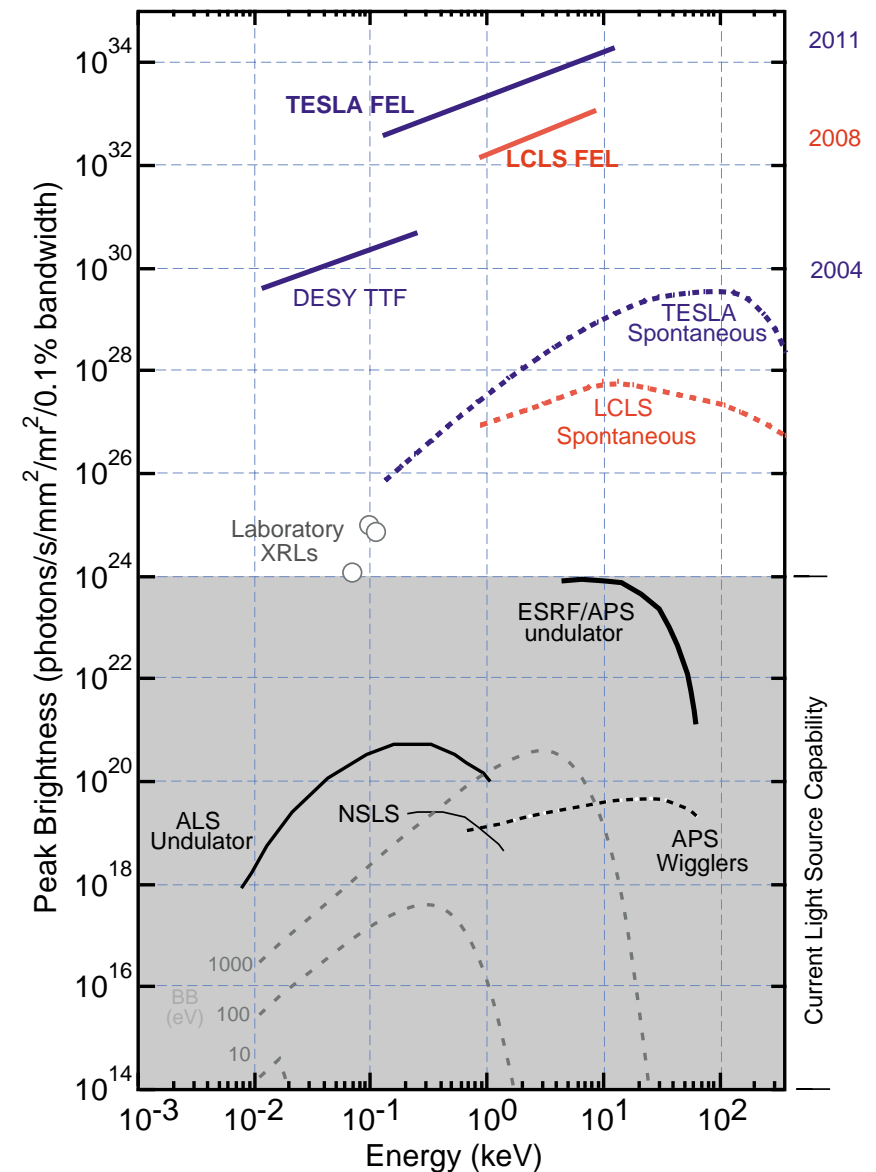
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Discussion is based future light sources; but, is applicable to intense short pulse x-ray sources

- Previous generations of light sources have been based on synchrotron radiation
 - Circular machines
 - High duty cycle (> MHz)
 - Tunable over wide energy ranges
 - Low number of photons per bunch
 - Long bunch duration (~ 50 ps)
- Next generation: Linac based
 - Short bunch duration (~ 100 fs)
 - Fully transversely coherent
 - Low repetition rate (~ 100 Hz)
 - Tunable
 - High peak brightness



XFELs are proposed for SLAC (LCLS**) and DESY (**TESLA**), DESY TTF is being upgraded**

- The specifications indicate that these are as much laser facilities as light sources

	TTF-II (6.0 nm)	LCLS (0.1 nm)	TESLA (0.1 nm)
mJ/pulse	0.3	2.6	3.7
Photons/pulse	9×10^{12}	2×10^{12}	2×10^{13}
GW	3	26	37
Peak Brightness	2.0×10^{30}	1.2×10^{33}	8.7×10^{33}
Bandwidth (%)	0.6	0.3	0.1
Hz	50	100	50
Date	2004	2008	2011

The case for short pulse x-ray based research is strong in several areas

- We will present only two topics relevant to LLNL:
 - **Creation and study of Warm Dense Matter**
 - **Probing Hot Dense Matter**

Finite Temperature High Density Studies

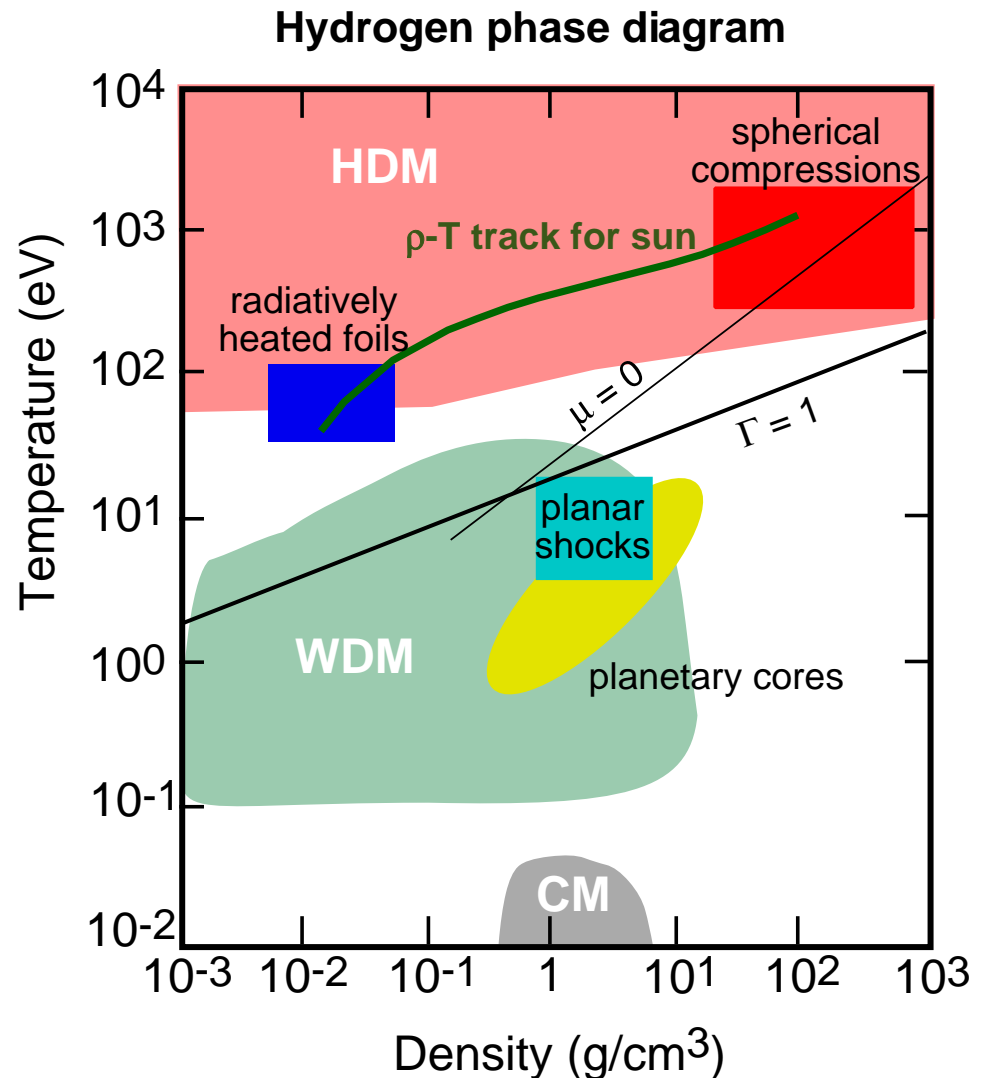
The importance of these states of matter derives from their wide occurrence

- Hot Dense Matter occurs in:

- Supernova, stellar interiors, accretion disks
- Plasma devices: laser produced plasmas, Z-pinch
- Directly driven inertial fusion plasma

- Warm Dense Matter occurs in:

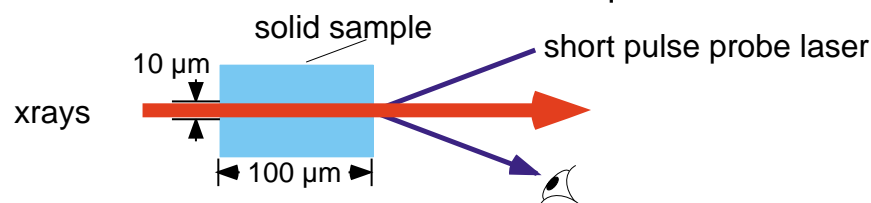
- Cores of large planets
- Systems that start solid and end as plasma
- X-ray driven inertial fusion implosion



Highlight three experimental areas in the high-density finite-temperature regime

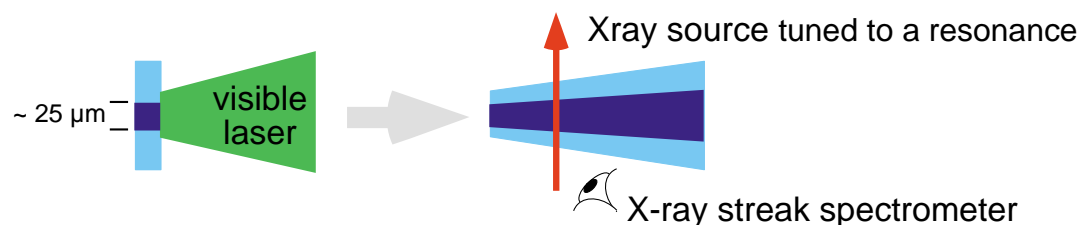
- Creating Warm Dense Matter

- Generate ≤ 10 eV solid density matter
- Measure the fundamental nature of the matter via equation of state



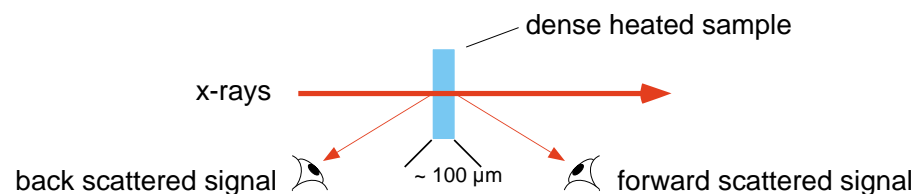
- Probing bound-bound transitions in Hot Dense Matter

- Measure kinetics process, redistribution rates, kinetic models



- Probing dense matter

- Perform, e.g., scattering from solid density matter
- Measure n_e , T_e , $\langle Z \rangle$, $f(v)$, and damping rates



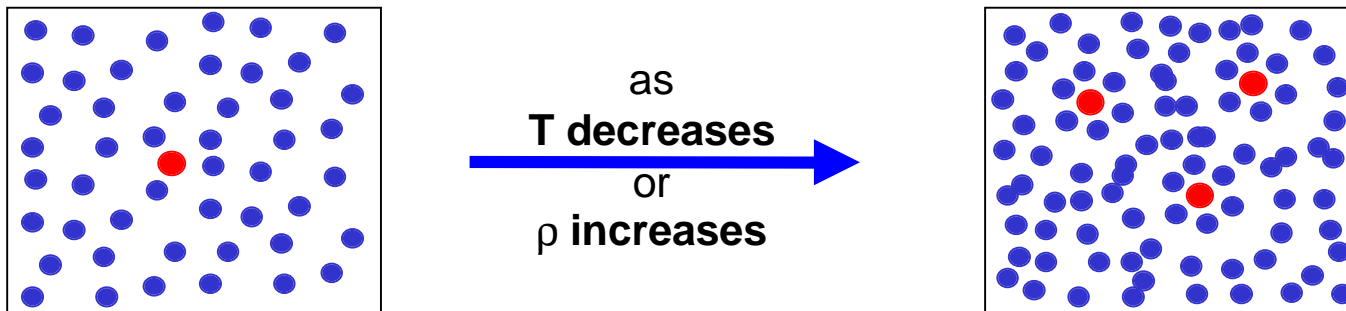
Intense short pulse x-ray sources can create and probe high-density finite-temperature matter

- To create Warm Dense Matter requires *rapid* uniform bulk heating
 - High photon numbers, high photon energy, and short pulse length \Rightarrow high peak brilliance
 - To pump/probe Hot Dense Matter requires a fast-rising short-duration source of high energy photons
 - Pump rate must be larger than competing rates
 - No laser source has flux (laboratory x-ray lasers or otherwise)
 - To measure plasma-like properties requires short pulses with signal $>$ plasma emission
 - No existing source can probe Hot Dense Matter
 - No existing source can create Warm Dense Matter to probe
-
- *Future FELs will be ideal as peak brilliance allows access to novel regimes*
 - *But, we need to start soon as possible*

Warm Dense Matter

From the point of view of a plasma the defining concept is *coupling*

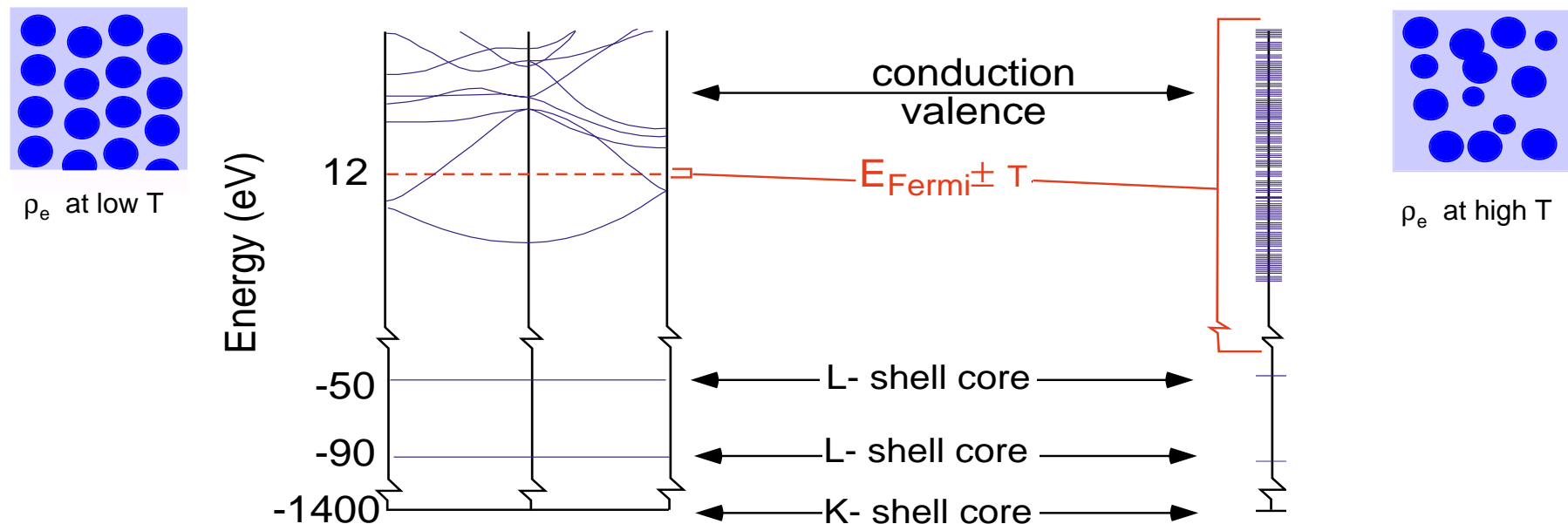
- Weakly couple plasmas are “easy”
 - The plasma can be seen as a separate point charges
 - Then the plasma is a bath in which all particles are treated as points - even particles with structure (e.g., atoms)



- But, when either ρ increases or T decreases:
 - Particle correlations become important
 - Ionization potentials are depressed
 - Energy levels shift

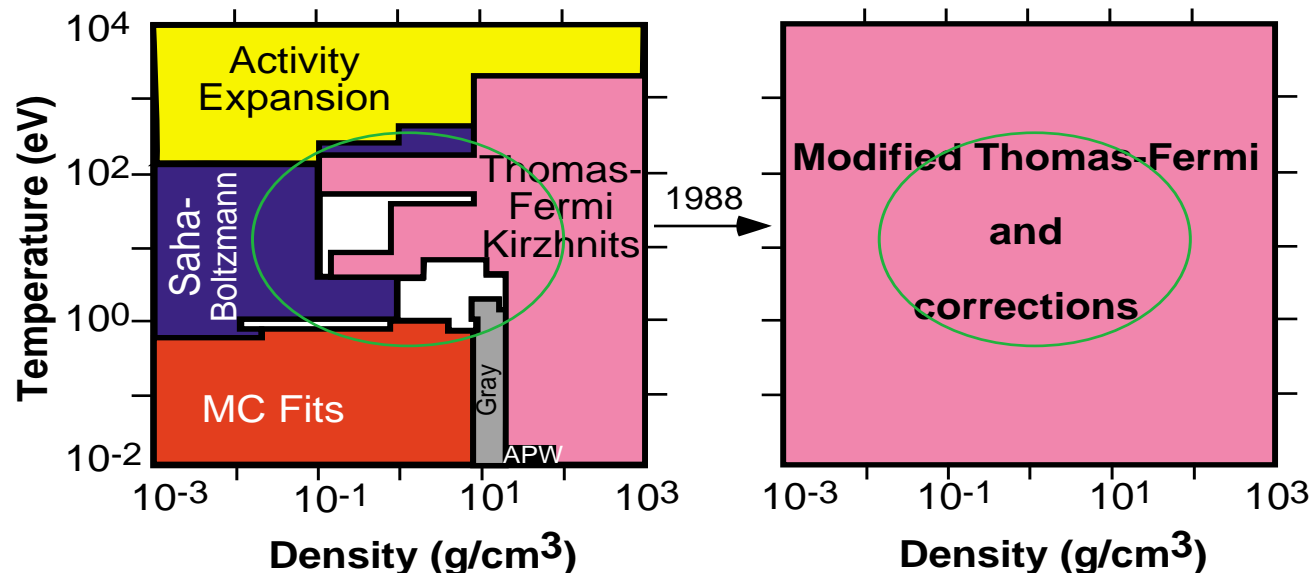
For condensed matter temperature relative to the Fermi energy defines WDM

- Fermi energy, E_{Fermi} , is the maximum energy level of an e^- in cold condensed matter
- When $T \ll E_{\text{Fermi}} = T_{\text{Fermi}}$ standard condensed matter methods work
- When $T \sim T_{\text{Fermi}}$ one gets excitation of the core
 - Ion- e^- correlations change and ion-ion correlations give short and long range order



WDM is theoretically challenging as there are no small parameters \Rightarrow data is critical

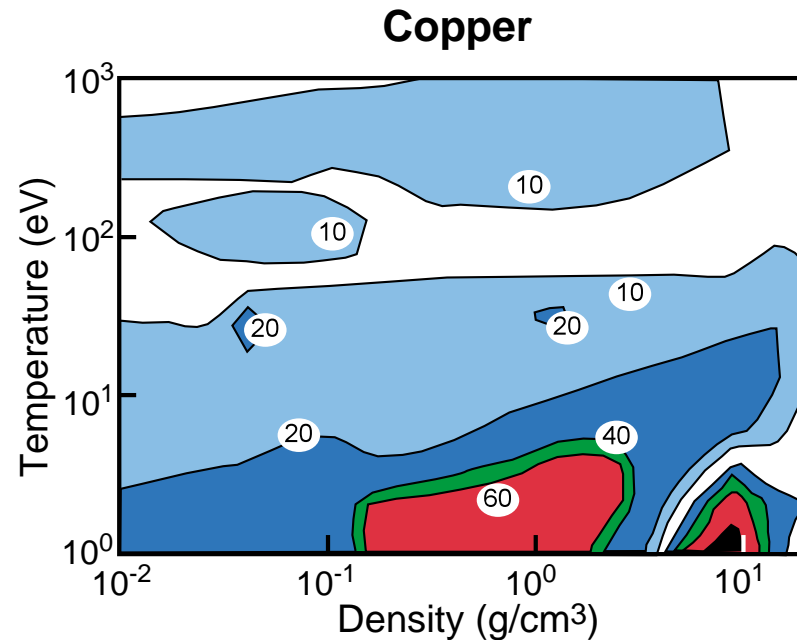
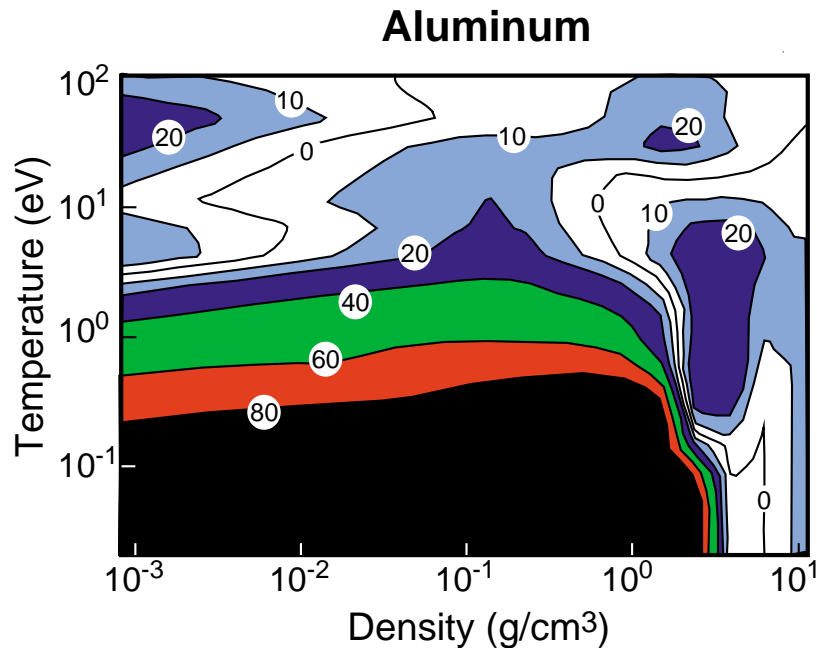
- WDM is the regime where neither condensed matter ($T = 0$) nor plasma theoretical methods are valid
- The Equation of State (EOS) of Copper indicates the problems



- Thermodynamically consistent EOS based on numerous schemes proved impossible (attempted from 1970's)
- A single incomplete description is now employed (from 1988)

In WDM regime large errors exist even for most studied materials

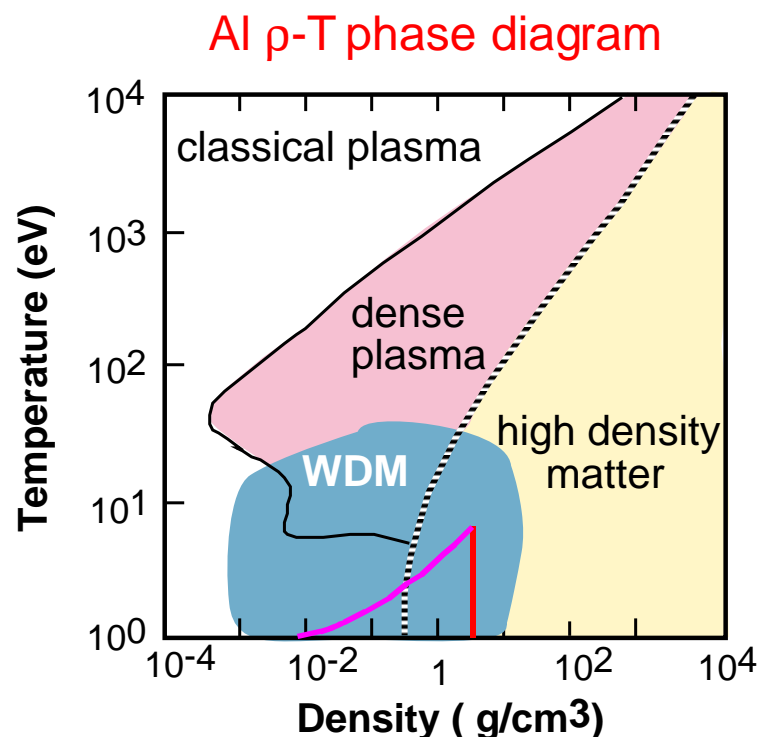
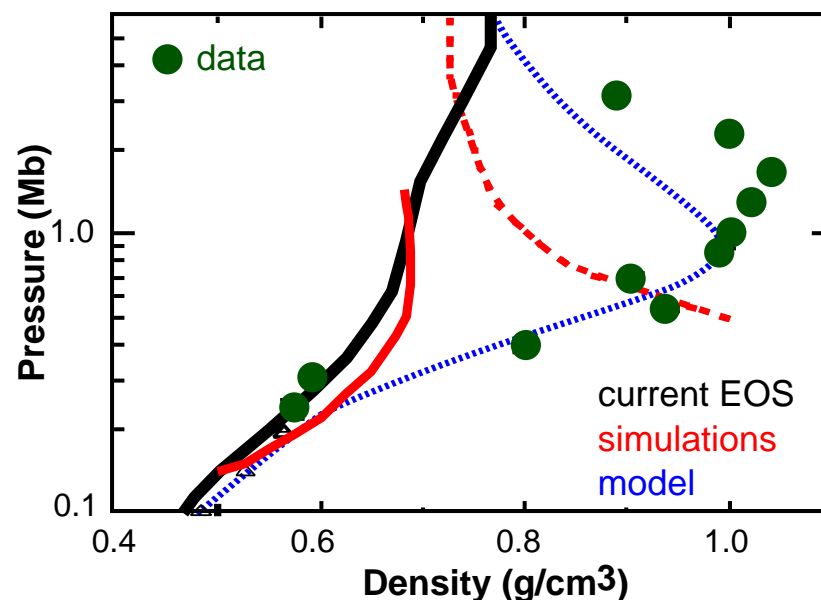
Contours of % differences in pressure



- Differences $> 80\%$ in the EOS are common
- Measurements are essential for guidance
- Where data exists the models agree!
 - Along principal Hugoniot: p - T - P response curve defined by single shocks

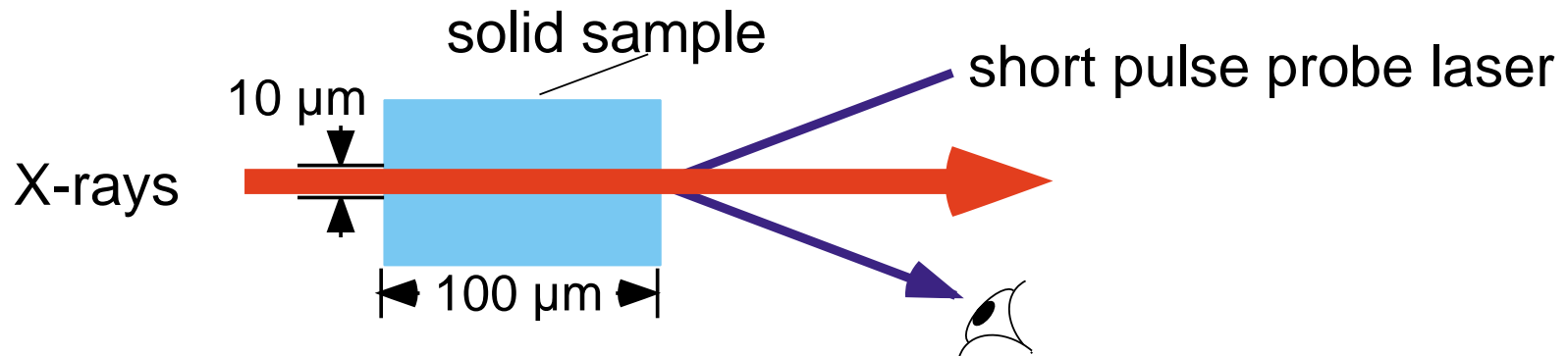
In WDM regime *data* leads to new results - short pulse x-ray sources will be critical

- Experimental data for D_2 along the Hugoniot shows theories are deficient



- An intense short pulse x-ray source can heat matter rapidly and uniformly:
 - creating **isochores** (constant ρ) and
 - release **isentropes** (constant entropy)

Intense short pulse x-ray sources can create WDM in a straightforward manner



- For a 10x10x100 μm thick sample of Al

- Ensure sample uniformity by using only 66% of beam energy
- Equating absorbed energy to total kinetic and ionization energy

$$\frac{E}{V} = \frac{3}{2} n_e T_e + \sum_i n_i I_p^i \text{ where } I_p^i = \text{ionization potential of stage } i - 1$$

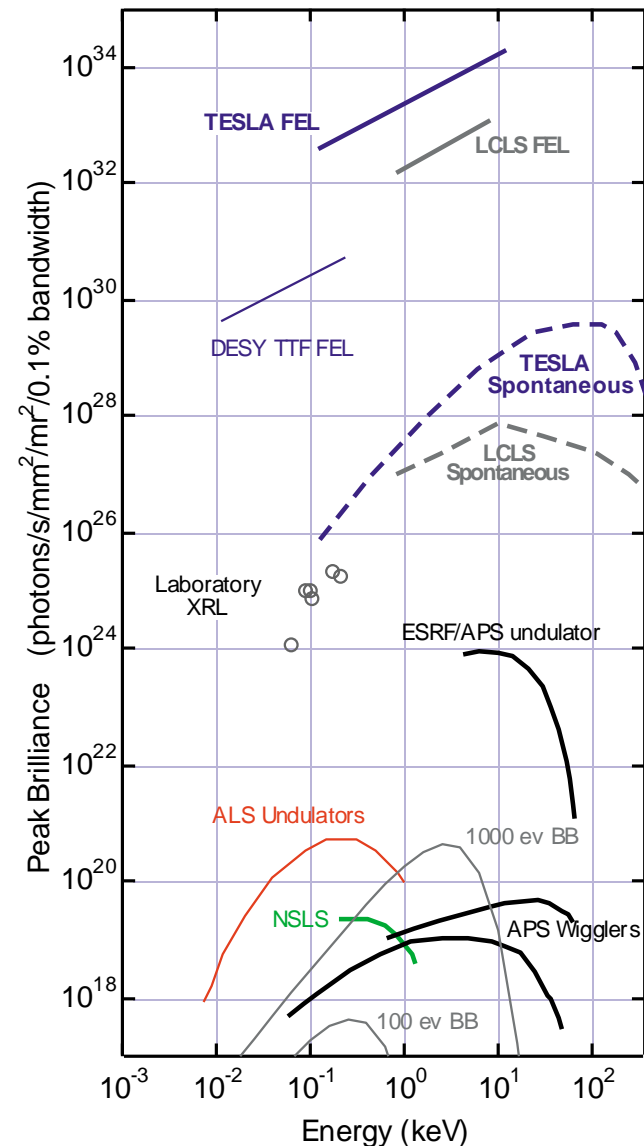
- Find 10 eV at solid density with $n_e = 2 \times 10^{22} \text{ cm}^{-3}$ and $\langle Z \rangle \sim 0.3$
- State of material on release can be measured with a short pulse laser
- Material rapidly and uniformly heated releases isentropically

Hot Dense Matter

(Plasmas)

For **Hot Dense Matter** intense short pulse x-ray source will generate unique results

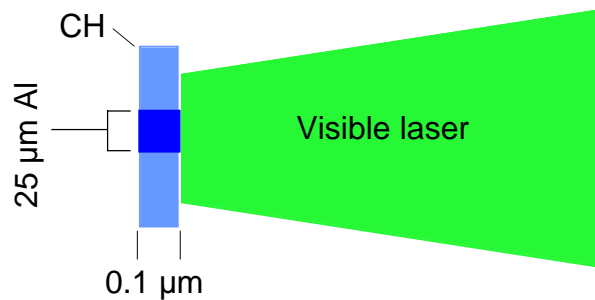
- For Hot Dense Matter the plasma collision rates and spontaneous decay rates are large
- To effectively move population, pump rate, R , must be $>$ decay rate, A
 $\Rightarrow R > A$
- For $I = 10^{14} \text{ W/cm}^2$ $R/A \sim 10^{-4} g_u/g_L \lambda^4$
 - FELs attain needed excitation strength
 $\lambda \sim 10 \text{ \AA} \rightarrow R/A > 1$
 - All Laboratory x-ray lasers are *insufficient*
 $\lambda > 100 \text{ \AA} \rightarrow R/A \ll 1$



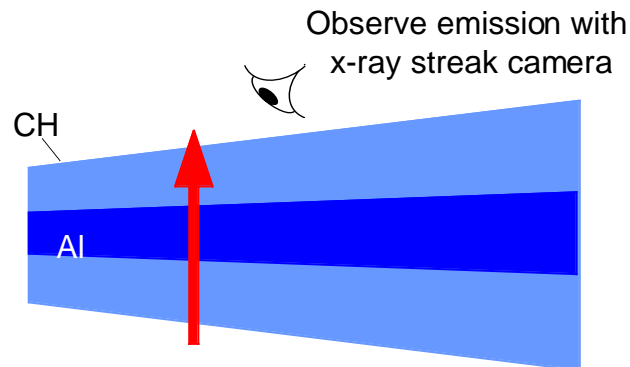
An X-FEL or XUV-FEL can photopump a transition: provides critical tests of plasma processes

• Experiment

- $t = 0$ laser irradiates Al dot

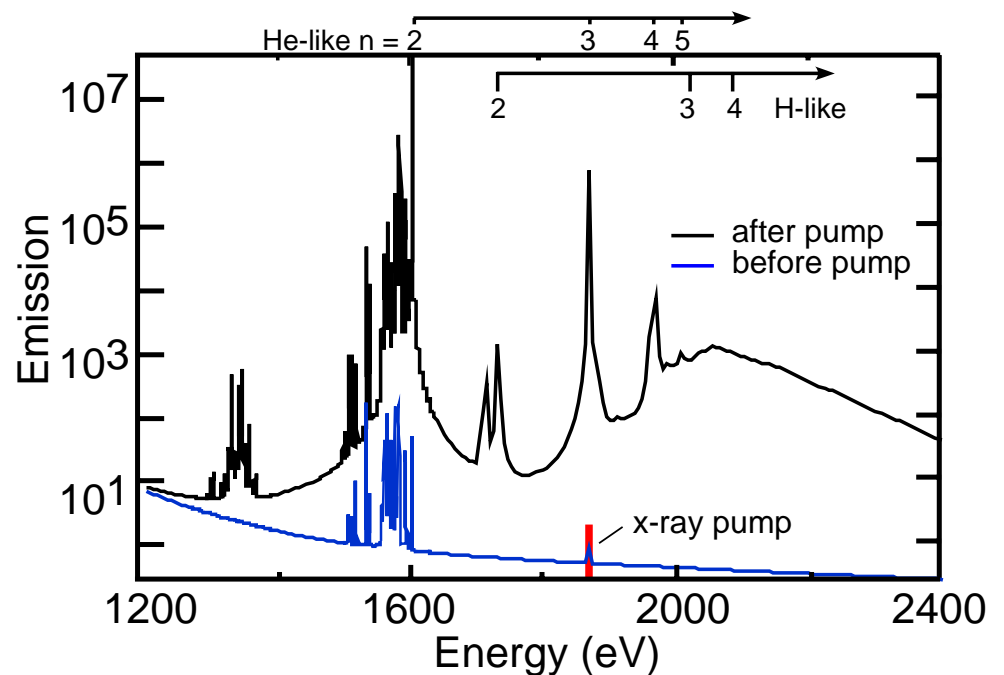


- $t = 100$ ps x-rays irradiate plasma



X-rays pump tuned to 1869 eV

• Simulation



Line intensity, line position, and line shape *may* be effected by strong coupling

- Simple form for emission illustrates the observable aspects

$$I(\omega) = N_{UL} A_{UL} \hbar \omega_{UL} \phi(\omega)$$

level populations

line shape

$$\phi(\omega) = \int d\varepsilon P(\varepsilon) J(\omega, \varepsilon) \quad \text{where } P(\varepsilon) \text{ is the ion microfield}$$

$$J(\omega, \varepsilon) \sim \frac{\text{Im}}{\pi} (\omega_{UL}(\varepsilon) + \delta(\omega) + i\gamma(\omega))^{-1}$$

- Investigate $\phi(\omega)$ and $\gamma(\omega)$ to look at effects on shape
- Investigate $\delta(\omega)$ to look at line position (shift)
- Investigate kinetics for effects on populations, n_i

Using an X- or XUV-FEL to pump within a line transition is fundamentally important

- Measuring redistribution within a Stark-broadened bound-bound profile
 - Assumption of complete redistribution within a profile can be invalid
 - ion field fluctuations
 - inelastic collisions
- Measuring the detailed redistribution of population by pumping within a transition can indicate relative plasma rate process

Ultimate test is the study of the radiation redistribution function $R(\omega_L, \omega_S)$

- I is the power spectrum of the radiation emitted at ω_S by a system pumped at ω_L

$$I(\omega_S, \omega_L) \propto \lim_{\eta \rightarrow 0} \text{Im} \sum_{i,f} p_i \left(\langle \langle \mathbf{V}_S | \mathbf{G}_W(i\eta) | \mathbf{V}_L \rho_0 \rangle \rangle \right)_{i,f}$$

V_S = interaction for emission
 V_L = interaction with pump
 G = resolvent of the evolution

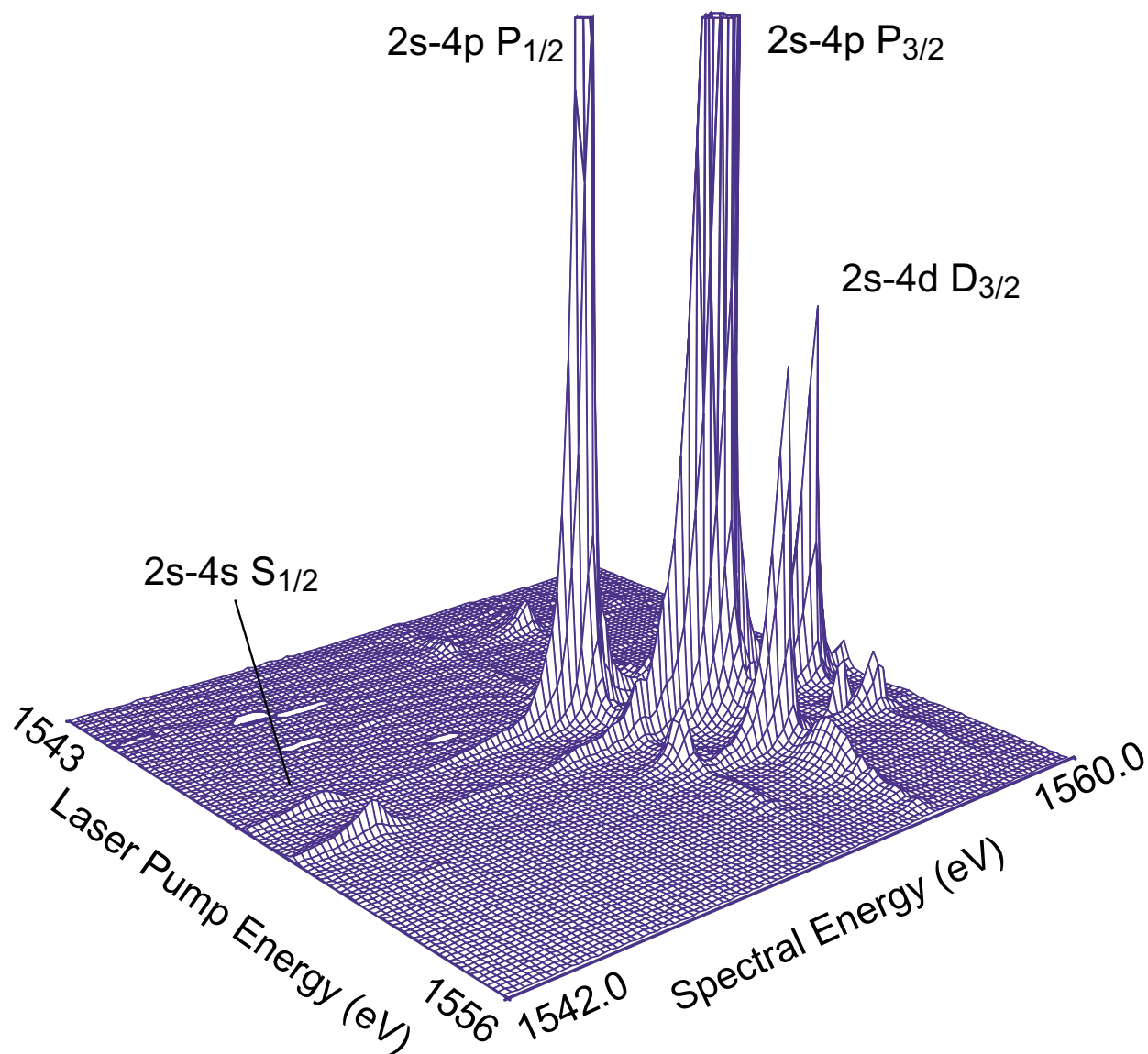
- $R(\omega_L, \omega_S)$ is the redistribution function

$$R(\omega_L, \omega_S) = \frac{I(\omega_L, \omega_S)}{\int \int I(\omega_L, \omega_S) d\omega_L d\omega_S}$$

- Investigate the redistribution using the X- or XUV-FEL

With bandwidth control and tuning, can pump within line to provide plasma rate data

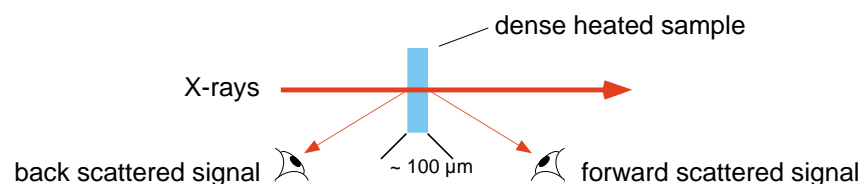
- Example:
pumping Li-like
Iron $1s^22l - 1s^24l$
- Collision rates
and plasma field
fluctuations can
be measured
- Bandwidth of
 $\sim 10^{-4}$ is easily
obtained by use
of a crystal



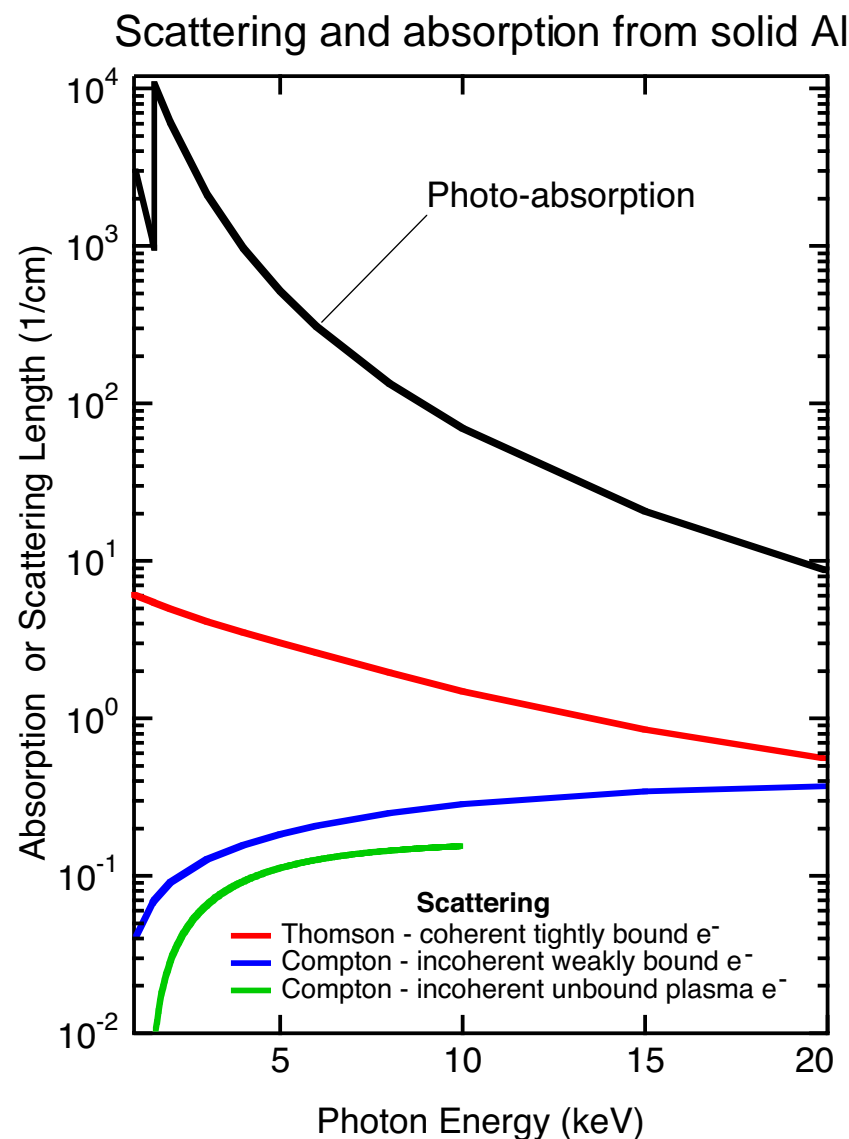
Probing

(only one example)

X- or XUV-FEL can be used to **probe** near solid density *finite* temperature matter

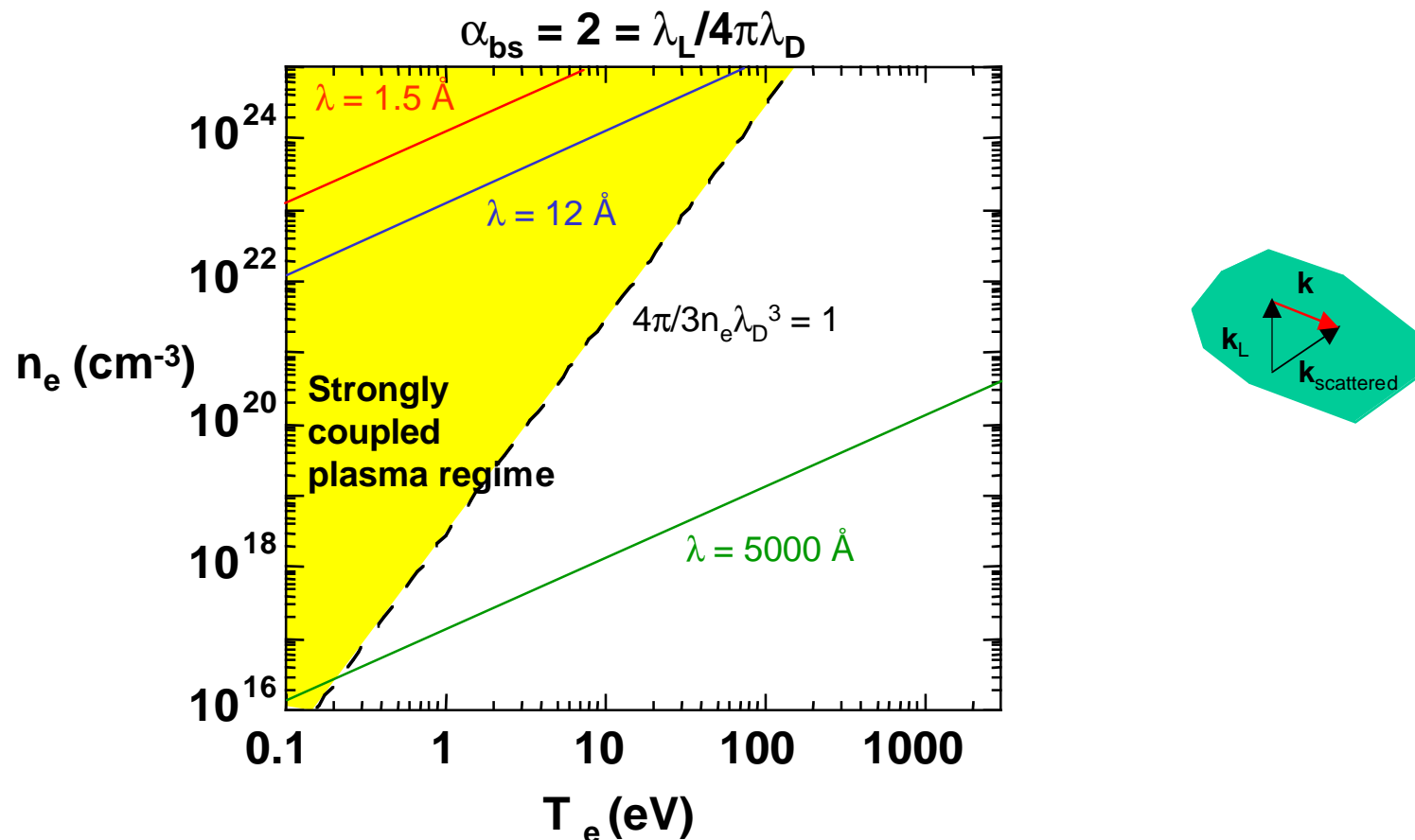


- Scattering from free electrons provides a measure of the T_e , n_e , $f(v)$, and plasma damping
 \Rightarrow structure alone not sufficient for plasma-like matter
- Due to absorption, refraction and reflection neither visible nor laboratory x-ray lasers can probe high density
 \Rightarrow no high density data
- X-FEL and XUV-FEL scattering signals will be well above noise for both Warm and Hot Dense Matter



Free electrons x-ray scattering accesses dense, strongly coupled plasma regime

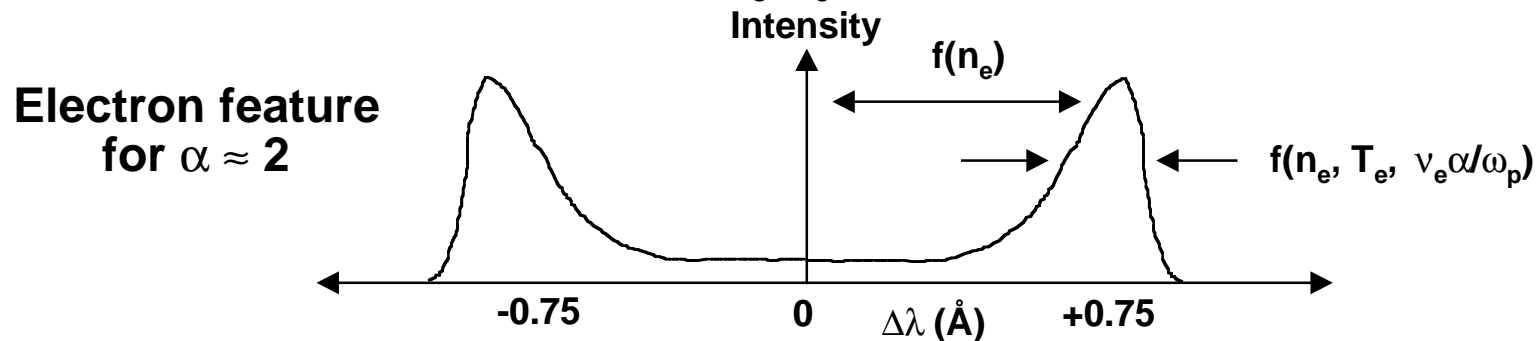
- The collective regime is probed for $\alpha = \lambda_L / 4\pi\lambda_D \sin(\theta/2) \geq 1$



- For $\alpha \approx 2$: n_e , T_e , collisionality ν_e and plasma flow data available from electron feature

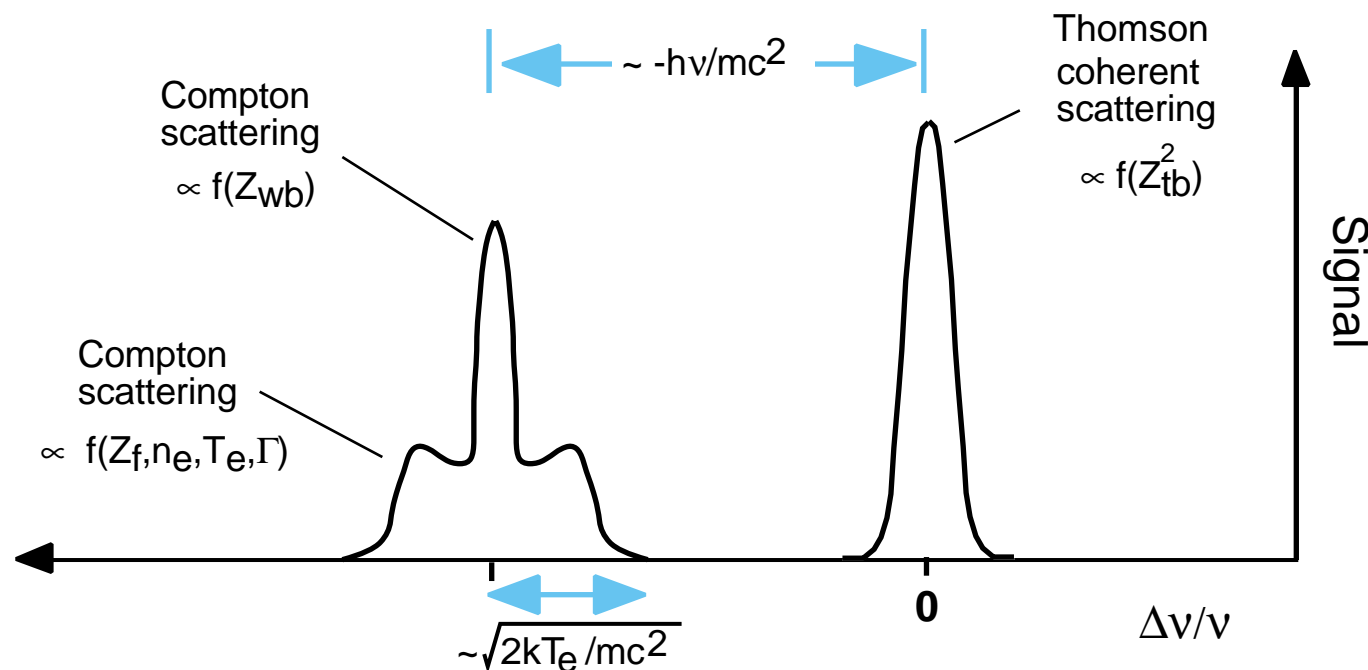
The XFEL provides a scattering probe of \geq solid density *finite* temperature matter

- X-ray laser output: at 12 Å $\sim 10^{12}$ photons
- Plasma probed: $n_e = 4 \times 10^{23} \text{ cm}^{-3}$, $T_e = 25 \text{ eV}$, $L = 10^{-2} \text{ cm}$
- Scattering parameter: $\alpha = \lambda / 4\pi\lambda_D = 12 \text{ Å} / (4\pi \times 0.6 \text{ Å}) \approx 2$
- Scattered fraction: $\sigma n_e L = 7 \times 10^{-25} / 2(1 + \alpha^2) \times 4 \times 10^{23} \times .01 \approx 3 \times 10^{-4}$
- Collected fraction: $\Omega / 4\pi \times \text{efficiency} \sim 4 \times 10^{-4} \times 10\% = 4 \times 10^{-5}$
- # photons collected: $10^{12} \times 4 \times 10^{-5} \times 3 \times 10^{-4} \approx 10^4$
- Signal / Planckian: $> 10^8$ for 300 μm probe size at $T_e = 25 \text{ eV}$
- $\Delta\lambda/\lambda$ required: $\Delta\lambda/\lambda \sim \sqrt{(n_e/n_c)/\alpha^2} = \sqrt{(4 \times 10^{23}/4 \times 10^{28})/4} \approx .006$



Scattering of an FEL will provide data on free, tightly-, and weakly-bound electrons

- Weakly-bound (wb) and tightly-bound (tb) electrons depend on their binding energy relative to the Compton energy shift



- For a 25 eV, $4 \times 10^{23} \text{ cm}^{-3}$ plasma the X-FEL produces 10^4 photons from the free electron scattering
- Can obtain temperatures, densities, mean ionization, velocity distribution from the scattering signal

Summary of Technical Program

Goals for Warm Dense Matter studies: measure EOS and plasma properties

- Equation of State measurements illuminate the microscopic understanding of matter
 - The state of ionization is extremely complex when the plasma is correlated with the ionic structure
- Other properties of the system depend on the same theoretical formulations
 - For example, conductivity and opacity

Goals for Hot Dense Matter:

study kinetics, line shapes, and plasma formation

- Since the advent of laboratory plasmas in the Hot Dense Matter regime quantitative data has been very scarce
 - The rapid evolution of high T_e and n_e matter requires a short-duration, high-intensity, and high-energy probe
- Short pulse intense x-ray sources will permit measurements of:
 - Kinetics behavior - test rates, model construction
 - Plasma coupling - measure directly $S(k, \omega)$, the dynamic structure factor
 - Line transition formation - measure line shapes, shifts, ionization depression
 - High energy density formation - measure matter in the densest regions

**Plan
for
WDM & Plasma-related
Research**

At recent Workshop on Warm Dense Matter a plan became clear for LLNL relevant interests

- Goal of the workshop was to develop an understanding of where the various capabilities (possibilities) fit in the picture
- Reports given on current and future experiments:
 - Light Sources
 - Ion Beam Facilities
 - Short Pulse Lasers Capabilities (SPL)
 - High Explosives Facilities
 - Gas Gun Facilities
 - Diamond Anvil Cell Capabilities (DAC)
- Reports given on current and future theoretical efforts

An overview of the conclusions

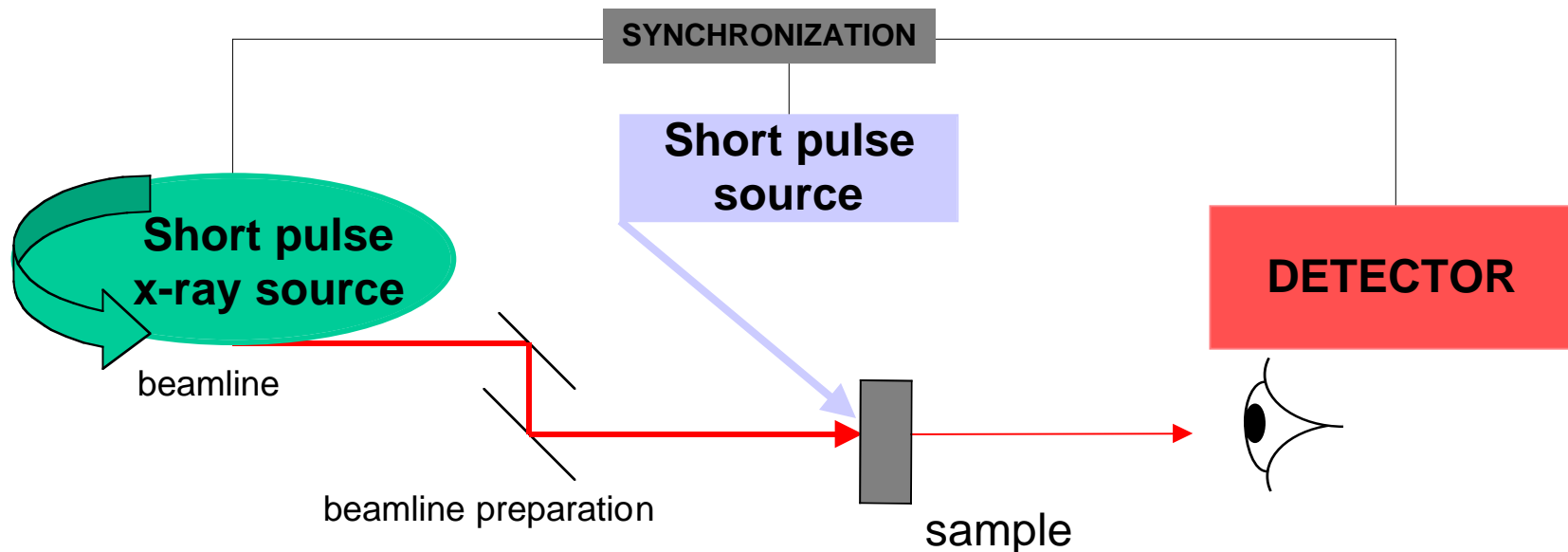
- The classic “high pressure” capabilities of DAC and Gas Guns do not make contact with the WDM regime
- The SPL capabilities have not produced any substantive results in the WDM regime
 - Over-promised
 - Under-performed
 - Project dissipated
- The rigorous requirements, of accuracy and volume of data, indicate large-scale user facilities will be essential
- The difficulties of developing techniques for these regimes indicate that SPL efforts should be intelligently pursued

The use of SPLs to develop techniques for user facility applications is important

- The first steps would be to devise relevant experiments at SPLs
 - Need to be concerned that the approach translates to the user facility
- Next, transfer the techniques to the light sources of the future:
 - Requires SPLs to be coupled to light source
 - Requires a short pulse intense x-ray source
 - Requires diagnostic development
 - OBTW: Requires investment from “us”
- Final stage will be the generation of data on a large scale

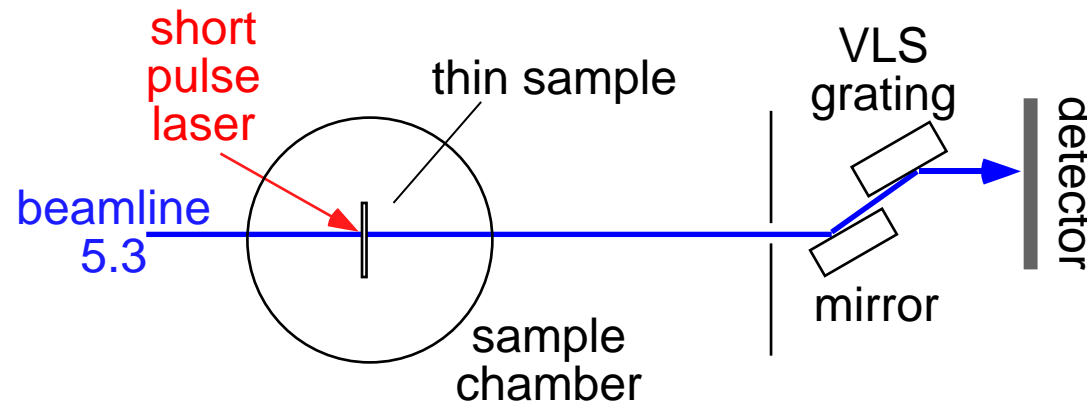
All WDM and Plasma-Related research have similar requirements

- One short pulse source to heat the sample to create the finite-temperature dense matter
- Another short pulse source to perform measurements
- Detectors capable of appropriate time resolution
- Synchronization of the ensemble



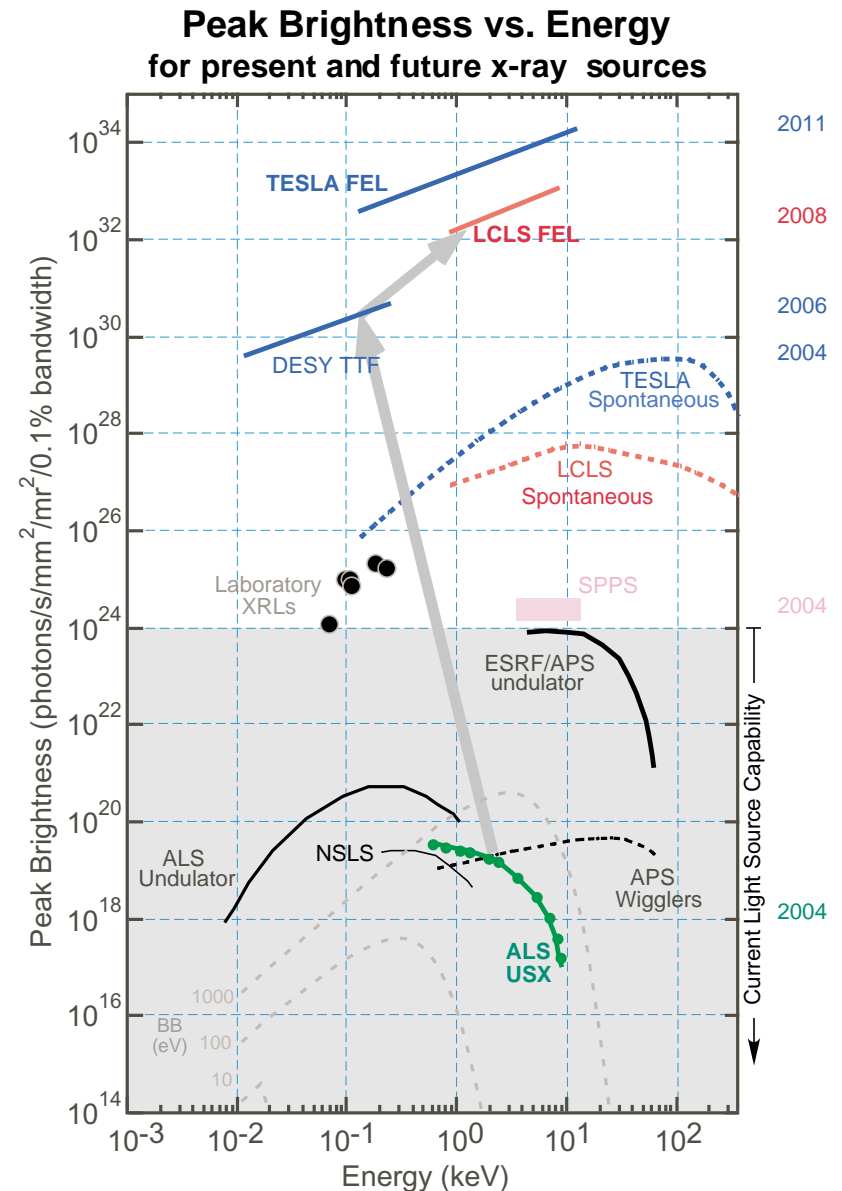
Plan can be illustrated by example: WDM experiment currently at ALS

- X-ray absorption of WDM sample
- Much preliminary work has been performed
 - Short pulse laser (150 fs) warms the sample
 - ALS probes warmed sample in the 100-200 eV spectral range
 - Time resolution is limited by ALS time structure
 - Or, if using a streak camera, by x-ray photon limitations



The path is defined by proposed facilities and each requires development

- “Move” experiment to ALS short pulse x-ray source
 - Provides time resolution of ~ 200 fs
- Move the experiment to the DESY TTF-II upgrade
 - Provides high peak brightness for potential heating and/or 200 fs probing
- Move the experiment to the LCLS X-FEL
 - Provides harder x-ray capability at high peak brightness
 - 200 fs probing and x-ray heating



Conclusions

- There is a need for data in the WDM and Plasma-related regime that can only be obtained at large scale facilities
- There is an understanding of how to develop a working series of experiments
 - Development on SPLs
 - SPLs coupled to short pulse x-ray light sources
- Proposed short pulse x-ray sources provide the path
 - ALS ultrafast “slicing” x-ray source
 - SPPS at SLAC
 - TTF-II upgrade at DESY
 - LCLS at SLAC and TESLA at DESY

Warm Dense Matter Conference and Experimental Planning Workshop at DESY

- **Warm Dense Matter Conference**

- JUNE 3-5, 2002

- **FEL Experiments Planning Workshop**

- JUNE 6-7, 2002

- Explore the possibilities for warm dense matter research at the Tesla Test Facility Phase II (TTF-II)

- Goal is to develop a proposal for a beamline

- **Contact: T. Tschentscher or R. Lee**